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Effect of beam shape and spatial energy distribution on weld bead geometry in conduction welding

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HIGHLIGHTS

- The spatial energy distribution have significant influence on weld bead geometry.
- Change of the beam shape at constant power and speed affects the energy density.
- Elongation of the beam in the processing direction results in deeper welds.
- Elongation of the beam in the transverse direction results in wider welds.
- Defocused beam provides higher peak intensity and penetration than focused beam.

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ABSTRACT

The size of a projected beam onto a workpiece and its intensity distribution profile defines the response of the material to the applied laser heat. This means that not only the processing parameters, but also the optical set-up and process tools define the process and the resulting weld profile. In high power laser delivery systems the beam propagation characteristics of the laser beam can vary during processing. A change of the focal distance, for instance, alters the spot size projected on the workpiece as well as its intensity distribution. Some dynamic optical systems can also change the shape of the projected beam. Galvo-scanners induce a small distortion to the projected beam from circular to elliptical when the mirrors deflect the beam across the working domain. This continuous change of the spatial energy distribution may affect the process stability and material response locally. This work examines the influence of changing the shape of the projected beam and its energy distribution on the weld bead profile in conduction laser welding, which is also relevant to laser cladding and additive manufacture. It has been found that for the same optical set-up and system parameters, different bead profiles can be obtained with different degree of distortion of the beam profile. In addition, different intensity distribution profiles led to different penetration depths for the same nominal beam diameter and energy density due to the difference in peak intensity.

1. Introduction

Laser processing is gaining on popularity in recent years. This has been possible because of the unique properties of lasers, which include directionality, non-contact operation and flexibility [1–3]. Amongst all, the main benefit of the laser is its ability to provide energy that can be controlled and focused to a specific area [4]. This leads to a precise source of energy, which is capable of achieving various processing regimes, including melting and vaporisation. Since a temporal and spatial energy distribution can be controlled, this allows the process to be tailored to a particular application [5].

It is common practice to change the focal position of a laser beam during processing [6,7]. This is often done to minimise spatter or to tailor the beam size to a particular case. However, this can also induce a change in the intensity distribution profile, e.g. from a top hat to Gaussian or a pseudo Gaussian depending on the optical set-up. Such a change will affect the thermal cycle and the resulting weld profile.

Conduction welding is one of the regimes of laser processing where the rate of applied energy does not allow the temperature to reach the boiling point of a welded material. In this regime the heat is absorbed at the surface and then transferred into the bulk of the material via thermal conduction. The lack of vaporisation leads to a relatively still

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melt pool and smooth, good looking aesthetically bead profiles. In terms of process control the main difference between keyhole and conduction regime is the energy density which is controlled by the beam diameter and intensity distribution profile [8,9]. Typically it is easier to deliver the energy required for melting but without exceeding the vaporisation temperature with bigger beam diameters. Condition regime is beneficial in all processes where a high surface quality and shallow penetration is required, such as conduction welding, laser cladding and additive manufacture.

In laser processing there are many sources of errors that can affect the bead profile. These errors are related to the hardware, e.g. beam delivery and optical set-up, processing parameters and material properties. In this study, the focus is put on the hardware. Fast translation of the laser beam across the working envelop is made possible with the aid of galvo-scanners [10]. However, deflection of a mirror in a galvo-scanner results in a continuous change of the beam profile on the workpiece during the processing. This is because the angle between the optical axis and the projection plain varies, as the laser beam is deflected, which results in elongation of its shape in the deflection direction. The extent of the beam deflection depends on the optical set-up and the deflection angle. Most galvo-scanners are equipped with an F-theta lens [11,12], which compensate for changes in the focal length as the beam is translated across the working domain, but it does not compensate for changes in the projected shape. Tang [13] examined the homogeneity of built parts by direct laser sintering with two rotating galvo-mirrors. Distortion of the projected spot size was identified as the most significant source of error in the built parts. The parts fabricated without any compensation exhibited significant deviation in the part dimensions up to 21% compared to the targeted dimension. This motivated the authors to develop a compensation strategy for correction of the spot size. This suggests that despite using the F-theta lens, the effect of distortion was very significant even for this small beam diameter of 0.6 mm. However developing a compensation strategy just by varying the laser power without understanding which energy parameters control the bead profile can a laborious task.

The bead shape and melting characteristics can vary in different regions of a powder bed, despite constant processing parameters [14]. This is partially caused by changing power density and spatial distribution of the laser energy caused by the continuous change of the beam shape across the working envelope of powder bed systems [15,16]. Random changes in the beam shape can induce changes to the interaction parameters i.e. power density, interaction time and specific point energy. Therefore, it is likely that in most galvo-scanner-based systems the processing conditions slightly vary in different regions of the processing domain. The relative error is the same irrespective of the size of the system, but the effect should be more evident for larger systems with longer focal length galvo-scanners.

In this work, the effect of distortion to the beam shape and its intensity profile on the bead profile in conduction laser welding has been investigated. The beam diameters used in this work are much bigger than in standard powder bed systems and are more relevant to laser cladding or welding, but on the other hand, the continuous drive to increase the size of additively manufactured components prompts development of bigger systems with larger area galvo-scanners. It has been shown that any significant increase in productivity is not possible entirely by varying just the process parameters and at a certain point larger beam diameters need to be used [5,17]. The challenge of beam distortion will become more significant with those large systems, hence this work should be relevant to additive manufacture as well.

2. Basic principle

Inclination of a laser beam with respect to the processed surface can result in a non-uniform beam shape and inconsistent bead profile during the melting process, as shown in Fig. 1. For example, a change of the beam inclination by 45° can cause a decrease of the power density by 30% and simultaneous increase of the interaction time by 40% due to the elongation of the beam, despite constant travel speed and laser power. This happens as the laser beam changes from the standard circular shape to an elliptical shape, with a greater surface area. The objective was to investigate the effect of spatial energy distribution on the bead profile when different beam shapes and energy distribution profiles are used but for the same nominal beam diameter. When the beam shape or size changes at constant laser power and welding speed, the energy conditions in the workpiece also change. The interaction parameters that determine the response in the material in conduction regime is power density and interaction time, given by Eqs. (1) and (2) [16].

$$\textit{Power density } (P_d) = \frac{\textit{Laser power } (P)}{\textit{Area of laser spot } (A_S)} (\mathrm{W\ m^{-2}}) \tag{1}$$

$$\textit{Interaction time } (t_i) = \frac{\textit{Laser spot diameter } (D_b)}{\textit{Laser travel speed } (v)} (\mathrm{s}) \tag{2}$$

The interaction parameters are controlled by the system parameters, which are settings changed by the operator using the laser control system. The system parameters include laser power, processing speed, beam diameter, beam shape, intensity distribution profile and temporal mode. But from the material perfective the process is controlled by the total amount of energy and the rate at which this energy is applied, as well as the domain over which this energy is applied, and this is specified by the interaction parameters [16].

3. Material and methods

3.1. Laser set-up

An IPGYLR-8000 continuous wave (CW) fibre laser with a maximum output power of 8 kW was used to produce a series of bead-on-plate welds. The laser beam delivery system consisted of an optical fibre with a diameter of 300 µm and a collimation lens with a focal length of 125 mm. To get different beam diameters a range of focusing lenses with focal lengths of 250 mm, 680 mm and 1000 mm was used. For every optical set-up the laser diameter and caustic was characterised using Primes Focus Monitor, which is a rotating pinhole beam profiler. The nominal beam diameter refers to a diameter of the beam according to the second order moment definition.

The material used for this study was S275 mild steel with size of 160 × 250 × 12 mm. The plates were cleaned with acetone to avoid organic contamination and coated with graphite to ensure constant absorptivity. The samples were clamped firmly and experiments were done without shielding gas. After welding the beads were cross-sectioned at a half-length and then polished and etched with 2% Nital prior to metallographic investigation. All cross sections were investigated under an optical microscope. For the measurement of melt area and penetration depth an image processing software AxioVision by Carl Zeiss was used.

3.2. Effect of shape of projected laser beam on weld bead profile

This experiment examined the effect of beam distortion and welding direction on the weld bead geometry in laser welding. The laser spot size was elongated by applying a tilting angle of 45° to the laser head. This was then compared with a reference sample achieved with a circular spot. All welding parameters and the change to the corresponding interaction parameters are given in Table 1. The power density and interaction time were calculated according to Eqs. (1) and (2). Note that in the case of the reference sample a small tilt angle of 5° was applied to protect the optical head from back reflection.

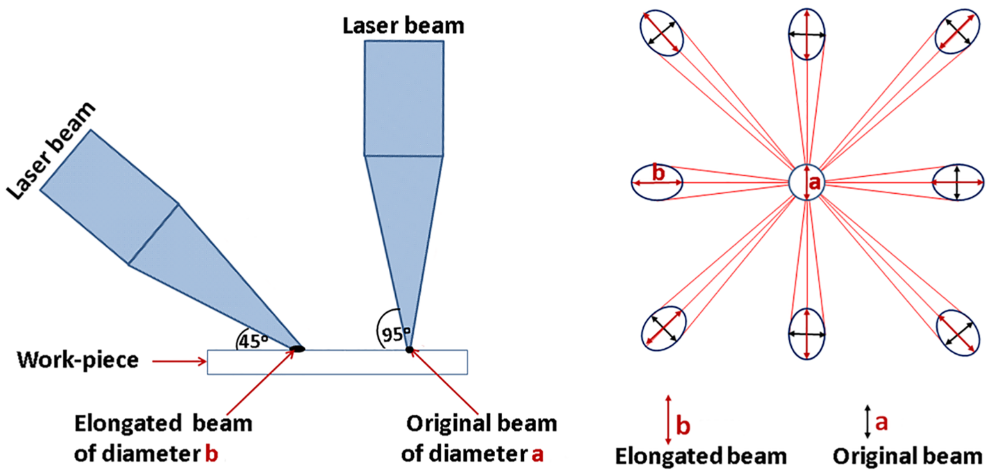


Fig. 1. Schematic representation of beam inclination and its effect on projected spot size.

3.3. Effect of intensity distribution on weld geometry

In this experiment welds achieved with out-of-focus beam were compared with welds achieved at the focal point for the same nominal beam diameters. The comparison was done at two different beam diameters. In the first case beam diameters of 1.70 mm and 2.35 mm were achieved by changing optical magnification of the processing head, meaning that for these welds the optics was in the focal points, which resulted in top-hat profiles. These welds are referred to as reference welds. In the second case another set of welds was achieved by using a 250 mm focusing lens but defocused in such a way to obtain the same beam diameters of 1.70 mm and 2.35 mm. The weld profiles were compared with the reference welds. In both cases, the same laser power was applied to obtain a power density of 17.8 kW/cm^2 for the beam of diameter of 1.70 mm and 33.1 kW/cm^2 for the beam of 2.35 mm. The change in focal distance resulted in a change in the intensity distribution across the beam from top-hat to a pseudo-Gaussian, as shown in Fig. 2. This enabled comparison between the welds achieved with the same nominal beam diameters and the same energy density but with different intensity distributions. The details are shown in Table 2. Each time the appropriate focus distance was achieved by inputting the right coordinates to the controller of the robot and the distance was additionally verified by measuring the distance between the processing head and the workpiece using a digital Vernier.

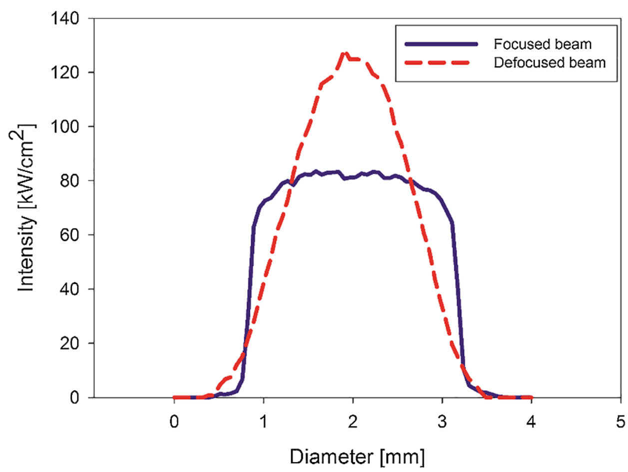


Fig. 2. Comparison of intensity distribution profiles between focused and defocused beams for the same nominal beam diameter of 2.35 mm and laser power of 3 kW.

4. Results

4.1. Effect of laser beam distortion on weld bead profile

In the first experiment, the laser beam was inclined at an angle of 45° and the resulting welds were compared with the reference welds. In Fig. 3 macrograph of the control sample is shown. This weld exhibits a uniform hemispherical shape typical for conduction welding. When compared to macrographs from Fig. 4, where the inclined beam (by 45°) was used with different travel directions, it can be seen that the weld shape and depth of penetration changed with the inclination angle and welding direction, despite the same welding parameters. When the beam is distorted, the projected laser spot becomes elongated in one direction, which changes the power density and energy distribution.

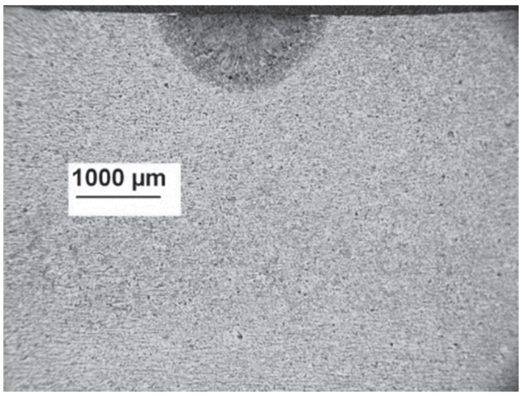
The effect of beam elongation on the weld bead profile is additionally complicated by the welding direction. The depth of penetration is higher for the welds produced with the elongation in the welding direction (direction 1), as compared to the elongation in transverse direction (direction 2). The former exhibits narrower weld width compared to the later. Therefore, the ratio of depth of penetration to weld width depends on the inclination angle and welding direction. Both the control sample and the sample with elongated beam towards the welding direction exhibit higher aspect ratio of depth to width, as compared to the welds elongated in the transverse direction. The shape of the control sample can be described as symmetrical, unlike in the cases of elongated beams, despite the same laser power and travel speed.

Table 1
Variation of power density, interaction time and energy density with inclination of the beam at constant laser power and travel speed.

Inclination angle (°)	Beam length in trans. dir (mm)	Beam length in travel dir. (mm)	Spot area (mm^2)	Power density (kW/cm^2)	Interaction time (ms)	Energy density (kJ/cm^2)
Reference	1.37	1.37	1.47	61.00	120.0	7.32
45	1.37	1.94	2.10	43.30	170.0	7.36
45	1.94	1.37	2.10	43.30	120.0	5.20

Table 2
Beam properties of different optical set-ups.

Focusing lens (mm)	Focus position (mm)	Beam diameter on workpiece (mm)	Rayleigh length (mm)	Laser power (kW)	Peak intensity (kW/cm^2)
250	+20	1.70	6.45	1.45	171.3
250	+28	2.35	6.07	0.80	44.0
680	0	1.70	37.48	1.45	94.19
1000	0	2.35	91.84	0.80	26.40



Depth = 0.73 mm, width = 1.76 mm and area = 0.77 mm^2

Fig. 3. Control sample (Depth = 0.73 mm, width = 1.76 mm and area = 0.77 mm^2).

4.2. Effect of energy distribution on weld profile

In this experiment, focused and defocussed beams were compared for the same nominal beam diameters and the same energy density. Significant difference in penetration depth can be seen in Fig. 5. In contrast the weld widths do not differ greatly, as shown in Fig. 6. The macrographs for the beam diameter of 2.35 mm are shown in Fig. 7. In both cases, greater penetration was achieved for the out-of-focus conditions, as compared to welding at the focal point. This is due to a higher peak intensity of the defocused beams [4]. A difference in depth of penetration of up to 12% for the beam diameter of 1.70 mm and up to 24% for the beam of 2.35 mm is shown in Fig. 7. This can be attributed to the difference in intensity distribution between focused and defocused beams.

5. Discussion

To melt a workpiece a certain amount energy is required. The weld bead in a particular material with a certain thermophysical properties is a result of the response of this material to a particular thermal cycle, which is determined by the spatial and temporal energy distribution of the heat source. To simulate distortion to the spot size induced by galvo-scanners and its effect on the bead shape, welding with inclined beam was investigated. As shown in Fig. 7, both the depth of penetration and weld width vary with the inclination angle and welding direction, due to the change in beam shape, despite using constant laser power and travel speed. This is consisted with previous study done by Tang [13].

The results from Figs. 3 and 4 indicate that different depths of penetration and bead widths can be achieved depending on the inclination angle and traveling direction. The difference is caused by the change in beam diameter, which then affects the interaction parameters of power density and interaction time. Elongation of a laser beam in the welding direction, at constant laser power and travel speed, results in a simultaneous decrease of power density and increase of interaction time, both of which affect the energy density. Similarly the reduced penetration depth in the transverse direction occurred due to lower power density, which for the same interaction time resulted in lower energy density (see Table 1). The main benefit of using inclined beam in the transverse direction was a wider bead profile. It was shown in previous studies that the depth of penetration in laser conduction welding is dependent on the interaction time and power density, the product of which is energy density [9,15,16]. Therefore, the reason why similar depths of penetration were achieved between the control sample and the welds produced with the beam elongated in the welding direction is because of constant energy density in both cases.

The extended interaction time due to the elongation compensated for the lower power density due to the increased area of the beam. Hence the energy density and the penetration depth stayed constant. Whereas in the transverse direction, the power density was reduced but at constant interaction time with respect to the reference sample, hence the drop in penetration. The weld width increased in this case because the width is mainly dependent on the beam diameter, which defines the size of the heat source. The concept of interaction time and power density could be used to develop a compensation algorithm to mitigate this effect.

The results are also consistent with the principle of conservation of energy. Since the total applied energy was the same between both inclination directions, the total melt volume also had to be the same, therefore, if the weld width increased in the transverse direction, the weld depth had to decrease. The difference in depth of penetration of up to 21% and in weld width of up to 43% between inclined and non-inclined beams suggests that the effect is significant. It is expected that this could be even more significant for bigger beam diameters. The inclination angle and the beam diameters used in this study are greater than in standard powder beds currently used, but they are representative for cladding and conduction welding. However the galvo-scanner used here is the same as in most commercial machines, therefore we can anticipate similar effect in real systems.

The use of the system parameters, such as laser power and travel speed is inadequate to characterise the weld bead profile in welding due to the effect of beam diameter. The weld bead profile in laser processing is dependent on the shape, power density and intensity distribution of the laser beam. The same spot size can be achieved with different power distribution profiles, hence different peak intensities. As shown in Figs. 5 and 7, this has significant influence on the weld profile. A laser beam used in the focal point resulted in a homogenous hemispherical weld bead, whilst a defocused beam resulted in deeper penetration and less uniform weld profile, despite the same nominal beam diameter and average power density.

The beam caustic for a particular optical set-up and the divergence of a laser source defines the optical propagation properties of the beam. In the imaging optical systems, in particular, such as used in most welding heads where the end of the fibre is imaged on the surface of the workpiece, the intensity distribution profile at the focal point is the same as at the fibre exit, which in most multi-mode fibres is a top-hat intensity profile. However in the far field, when the beam is defocused beyond the optical depth of focus the intensity profile changes to a pseudo-Gaussian. In that case the same average power density is achieved but with much higher peak intensity to ensure the same area under the intensity profile, as shown in Fig. 2.

This higher peak intensity in the centre, with gradually decreasing power towards the circumference of the laser spot results in a rapid

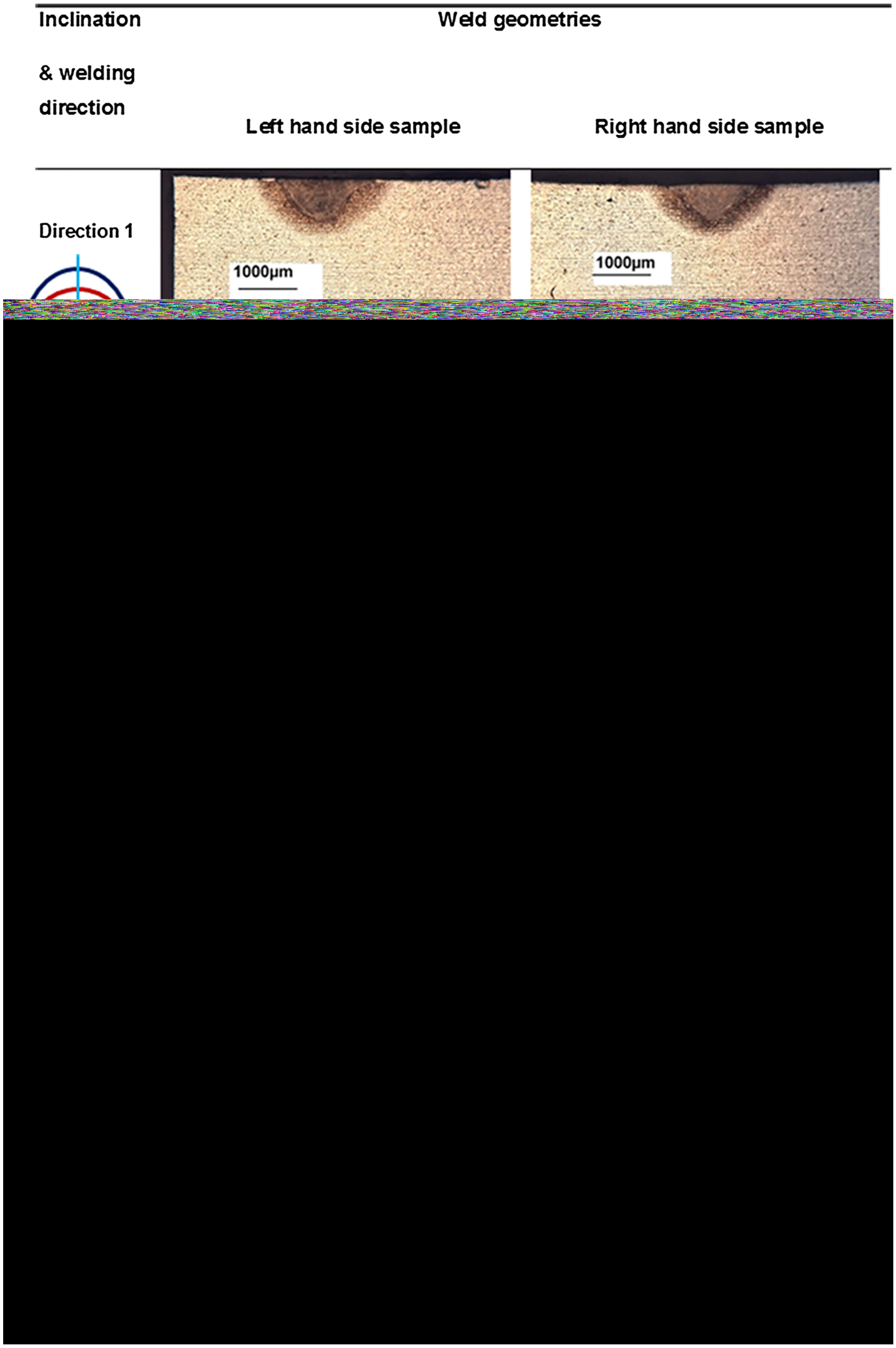


Fig. 4. Bead-on-plate welds produced at an inclination of 45°, laser power of 0.9 kW and travel speed of 0.69 m/min (The light blue line indicates the welding direction, the royal blue circle is the elongated beam and red circle is the original beam). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

thermal gradient with high temperature in the central part, which can exceed the melting temperature of the material in the central region sooner than a top-hat beam with a uniform intensity distribution. The maximum temperature reached in the melt pool, which is a function of absorbed power density, affects the weld geometry during laser welding. It is expected that the temperature reached with a Gaussian beam profile having greater intensity is much higher than with a top hat beam for the same average power. This could also potentially lead to a greater absorptivity, which increases with temperature. Therefore, the depth of penetration with Gaussian beams should be higher than with top hat beams, as shown in Fig. 7.

However, at a certain distance from the centre of the Gaussian beams, the intensity decreases more rapidly than for top-hat beams, hence the effect is not always easy to observe. In addition, the rapid temperature gradient of Gaussian beams is homogenised by the melt pool, which mitigates the difference between both cases. This

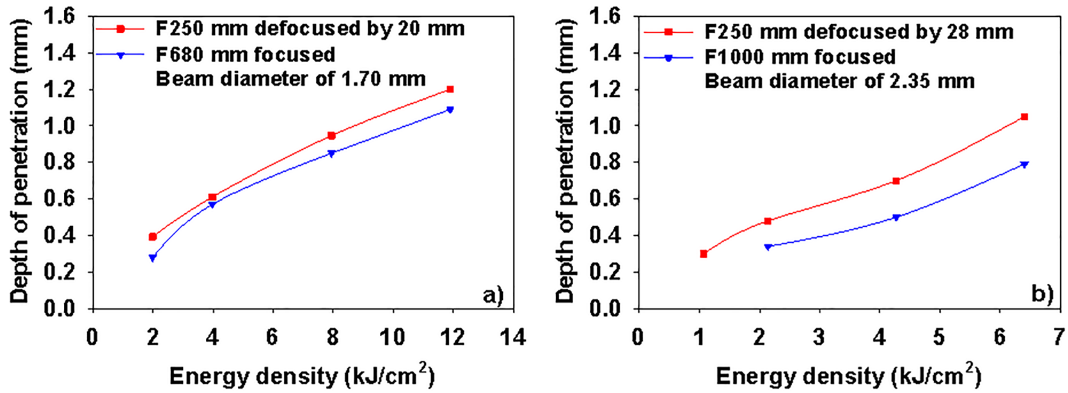


Fig. 5. Comparison of depth of penetration between focused and defocused beams at constant nominal beam diameters; (a) nominal beam diameter of 1.70 mm; (b) nominal beam diameter of 2.35 mm (constant power and travel speed).

homogenisation ability of the meltpool explains why the difference in weld profiles between the weld achieved at the focal point and at the weld achieved with defocused beam is lower for small beam diameters. For the beam diameter of 1.70 mm (power density of 33.1 kW/cm^2) (Fig. 5a) the difference in depth of penetration is lower compared to beam diameter of 2.35 mm (power density of 17.8 kW/cm^2) (Fig. 5b). The smaller the beam diameter the higher the average power density, which should lead to greater temperature gradient, but this gradient induces more dynamic convection, which self-balances the system. Therefore the difference in weld profiles is less significant for small beams. This was also demonstrated in previous studies in keyhole laser welding, which typically requires higher power density and smaller beam diameters [18,19].

In future work we will carry out similar experiments in a powder bed system to investigate the effect of intensity distribution and distortion of the beam shape on the bead profile of deposited tracks. However due to inhomogeneous properties of powders it is more challenging to capture those effects than in solid materials.

6. Conclusions

Influence of the inclination angle of a laser beam and hence its projected shape on the resulting weld profile was investigated. This simulated changes to the spot size induced by galvo-scanners. In addition, intensity distribution was changed by comparing focused and defocused beams for the same nominal beam diameter. The following be concluded from this study:

- Elongation of a laser beam affects the resulting weld profile in conduction welding. Elongation in the welding direction increases the beam length, which then results in longer interaction time and simultaneously larger crosssectional area of laser spot and hence lower power density. Therefore, the resulting welds exhibit the same penetration depth, as compared to the circular beam. The effect is additionally dependent on the traveling direction with elongated beams. Elongated beams in the welding direction result in deeper and narrower welds than corresponding welds achieved with beams elongated in the transverse direction. This may raise concern related to the use of galvo-scanners in cladding, welding or additive manufacturing.
- Power density distribution of a laser beam has significant influence on the weld profile in conduction welding. A defocused beam with a pseudo-Gaussian intensity profile resulted in deeper welds than a focused beam with a top-hat profile for the same nominal beam diameter. This means that changing the beam diameter by adjustment of the focus position may result in different weld profiles.

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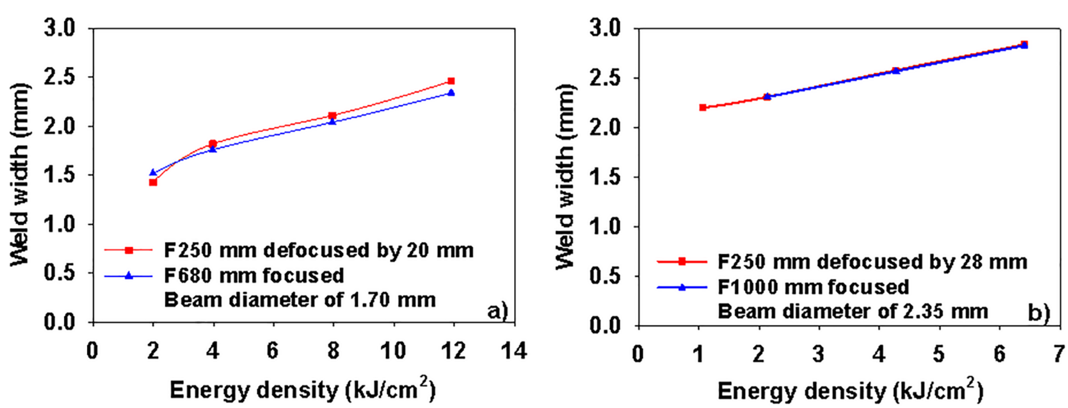

Fig. 6. Comparison of weld width between focused and defocussed beams but at constant nominal beam diameters; (a) nominal beam diameter of 1.70 mm; (b) nominal beam diameter of 2.35 mm (constant power and travel speed).

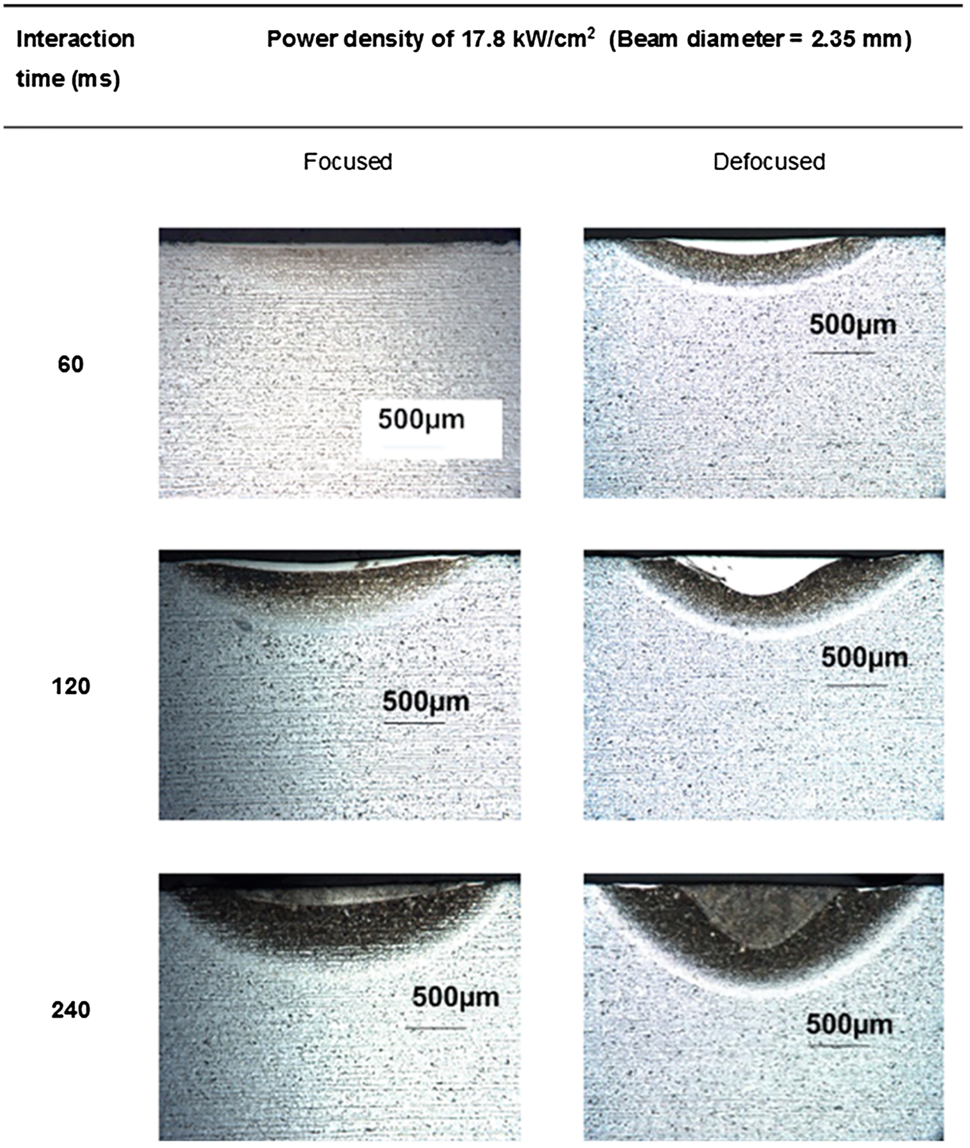

Fig. 7. Comparison of welds produced at constant nominal beam diameter but one produced at the focal point and another in out-of-focus conditions.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.optlastec.2019.04.025.

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